

Interrupted Time Series Methods for Public Health Interventions

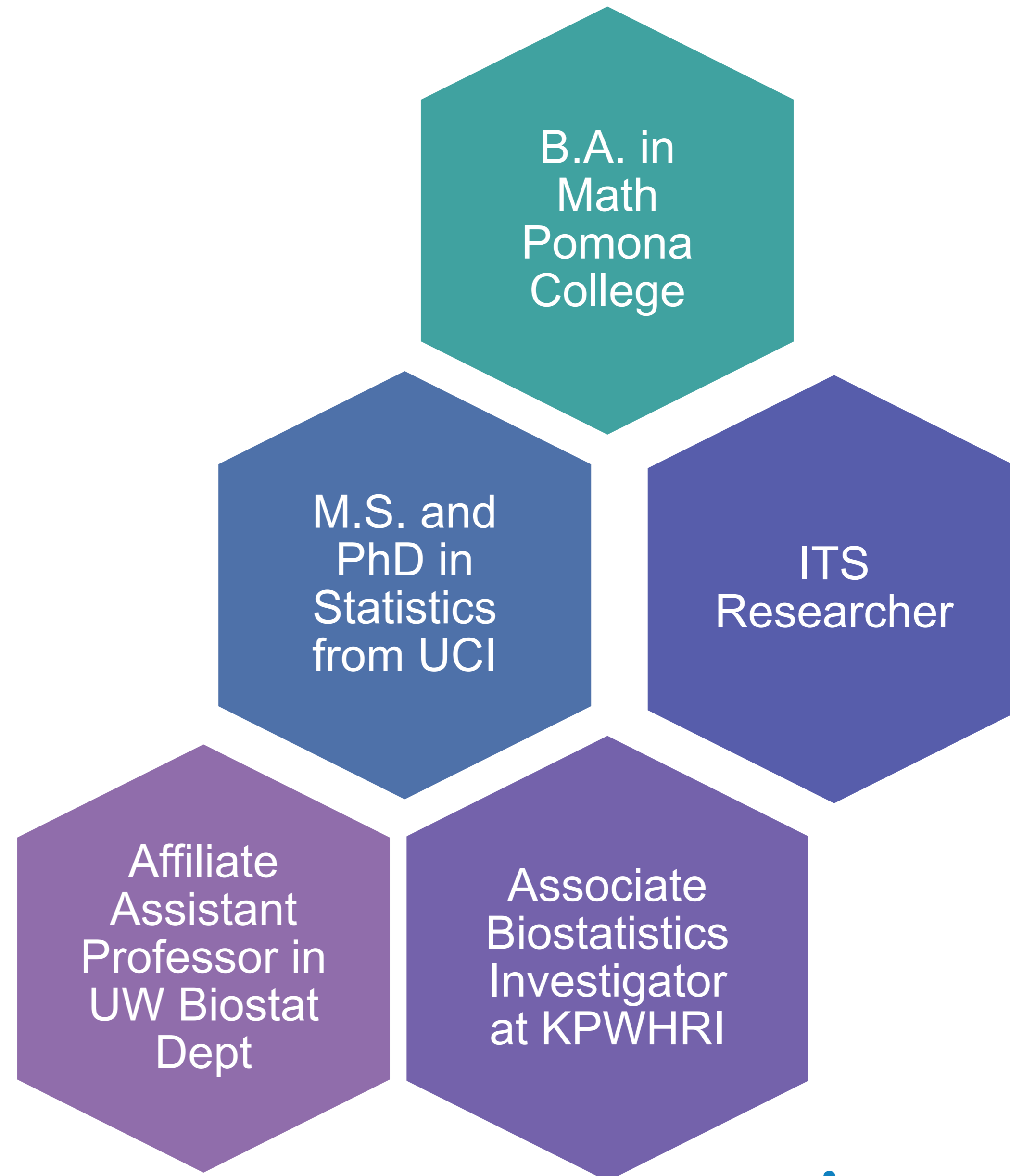
Maricela Cruz | April 24th, 2026

About Me



Professional About Me

- Applied areas of research
 - Mental Health, Health Equity, Healthy Communities, Nursing
- Statistical research
 - Develop statistical methods to evaluate the impact of complex healthcare interventions in observational settings



Agenda

- Introduction to Interrupted Time Series (ITS) \approx 40 min
- Break \approx 5 min
- Small Group Exercise #1: Evaluate a study that used an ITS design \approx 15 min
- Break \approx 5 min
- Small Group Exercise # 2: Design an ITS study \approx 15 min

Disclaimer: I work in mental health settings. I will mention self-harm on slide 26 and 27.

Need for Interrupted Time Series (ITS) Methods

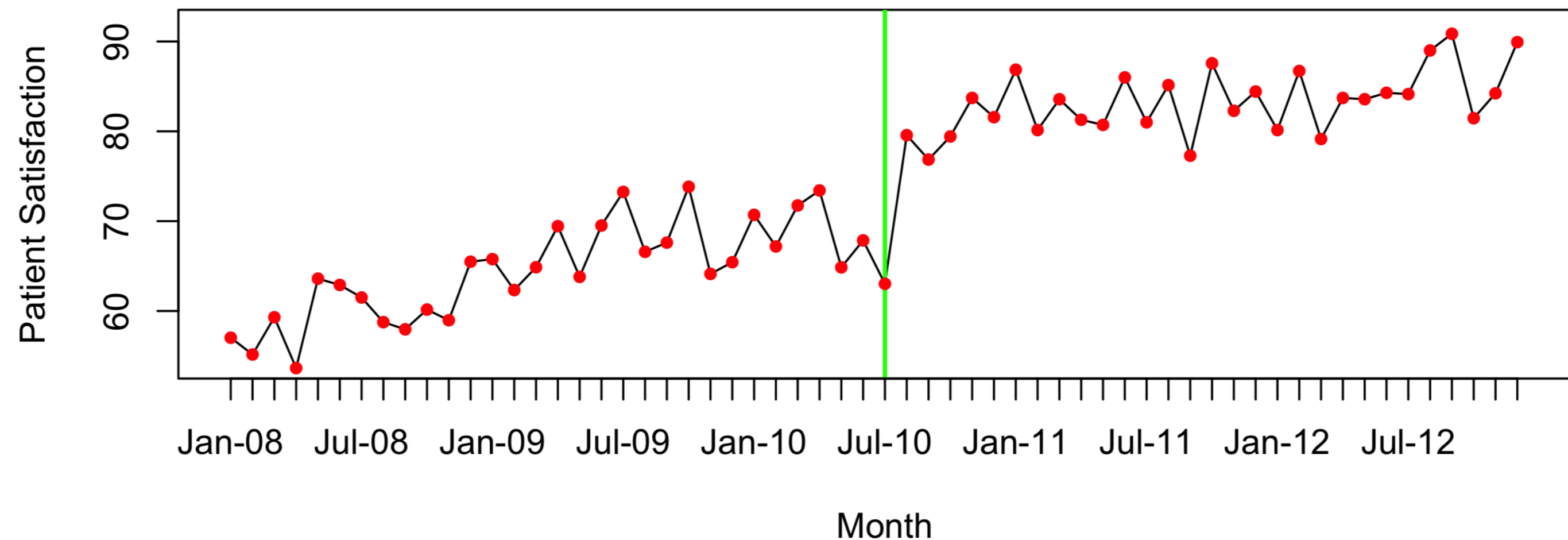
- Evaluating effectiveness of complex interventions on patient-centered outcomes is a growing concern
- National U.S. organizations financially incentivize public health reform
- Assessing the impact of public health interventions is difficult
 - Cohort and case-control studies are less useful
 - Randomized controlled trials are often not feasible
- According to the 2018 Annual Review of Public Health:
 - ITS designs may be the only feasible recourse for studying the impacts of large-scale public health policies

ITS Designs vs. ITS Data vs. ITS Methods

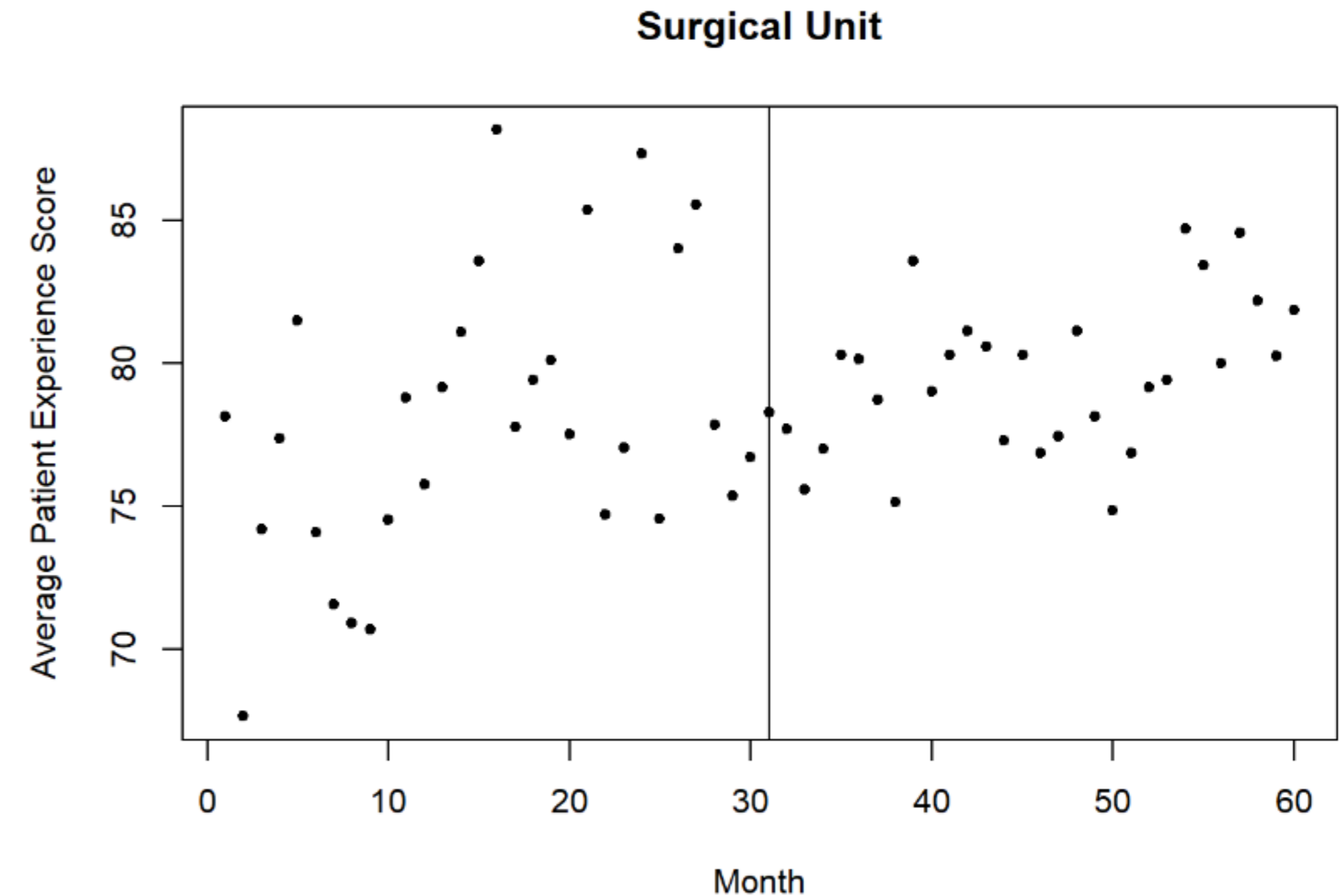
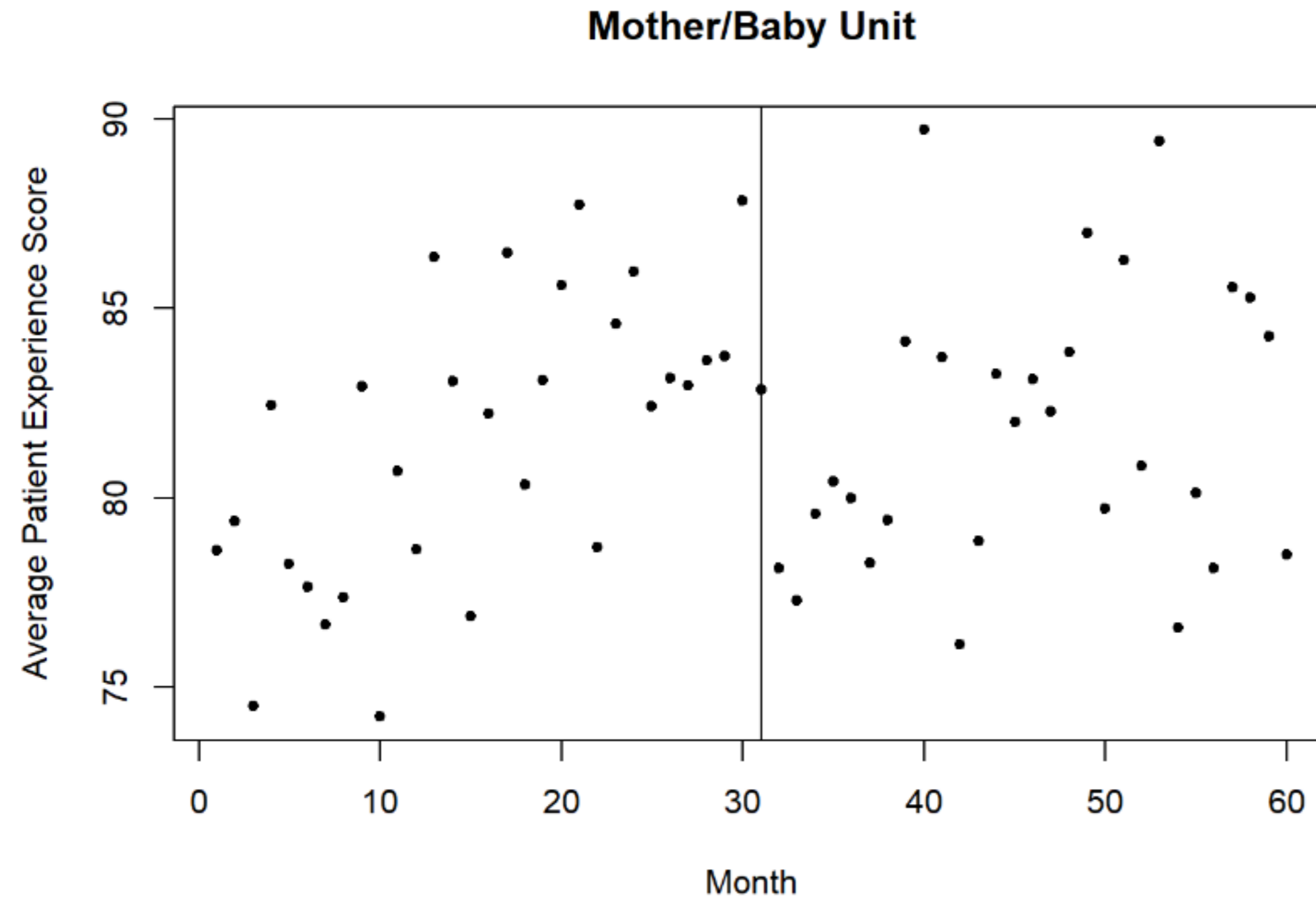
- ITS Designs
 - Natural experiments
 - Borrow from traditional case-crossover designs
 - Function as quasi-experimental methodology for population-level inference
 - Able to retrospectively analyze the impact of an intervention
- ITS Data
 - Data from a study with separable pre- and post-intervention periods
- ITS Methods
 - Statistical methodology used to analyze ITS data

When are ITS designs appropriate?

- ITS designs require:
 - Complete separation of the pre- and post-intervention periods
 - A known change point or set of possible change points
 - An outcome impacted by the intervention
 - One time series/outcome
 - Enough measurements pre- and post-intervention to estimate model parameters



Why are ITS Designs the 'Strongest' Design for Observational Studies?



Controls for secular trends/history, establishes a pre-intervention baseline, and the population serves as its own control

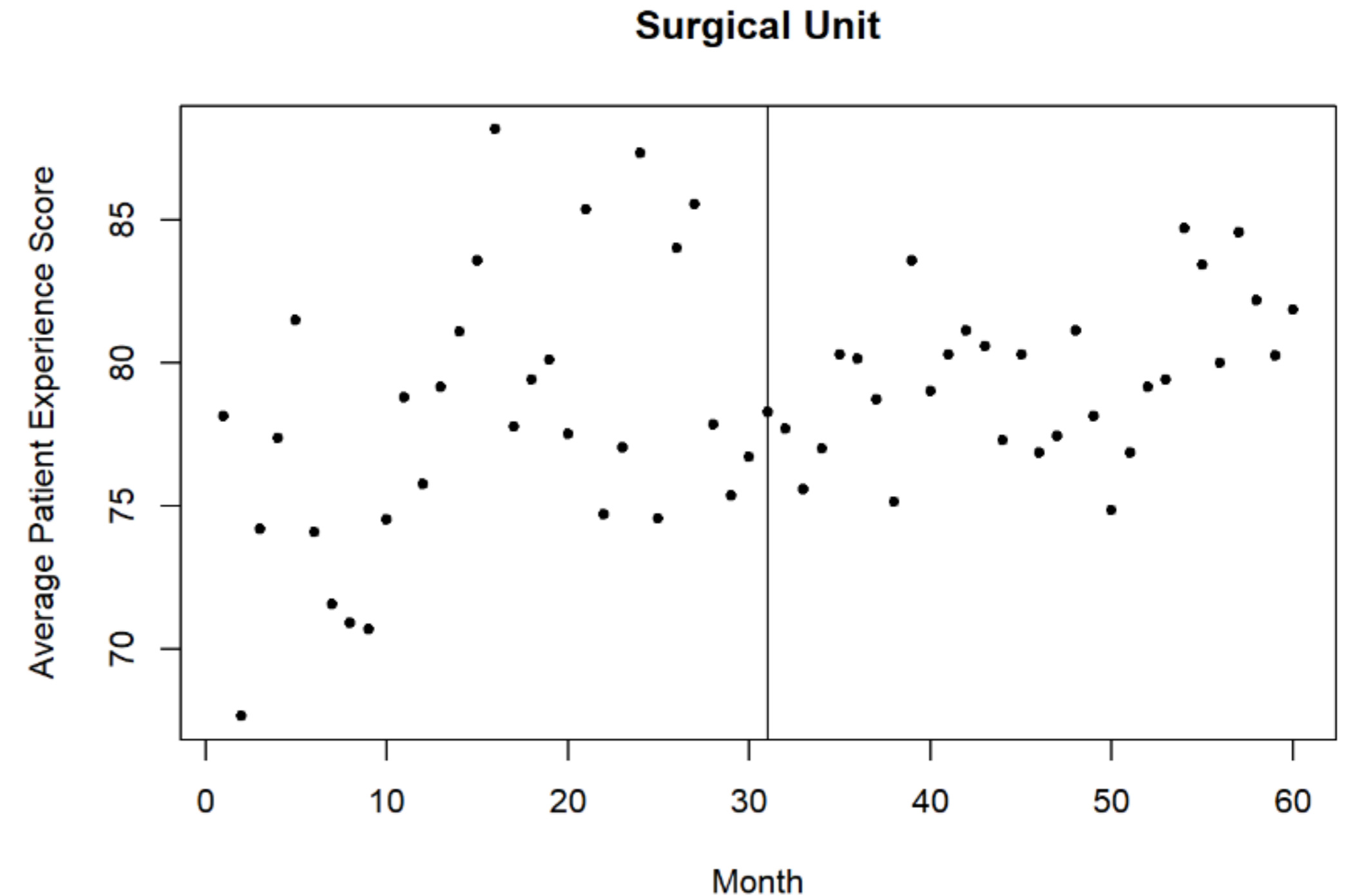
Measures immediate and long-term changes (and changes in 'predictability')

Public Health Intervention Data

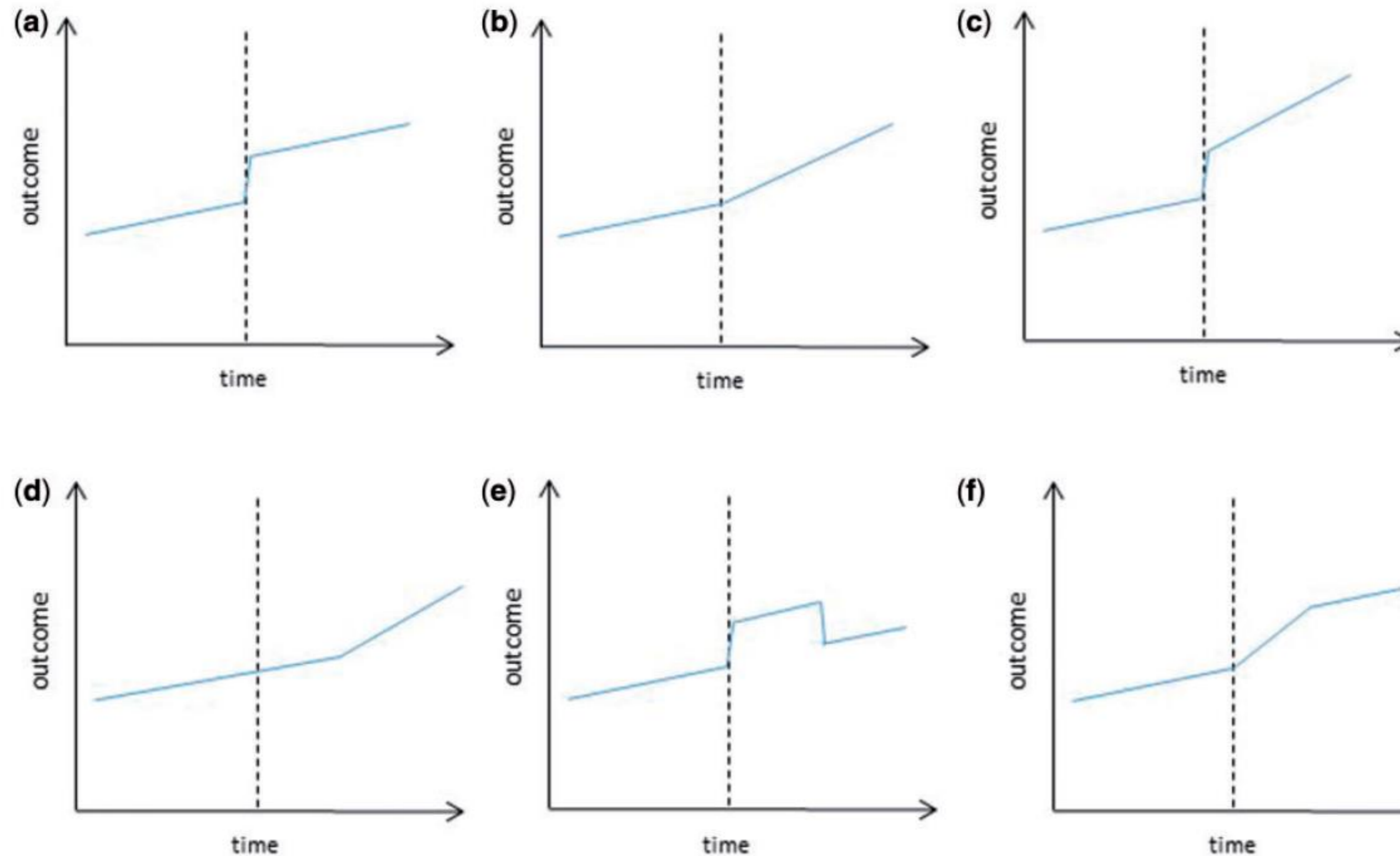
- Intervention data often present as ITS data:
 - Sequences of measurements for an outcome (e.g., patient experience scores)
 - Collected at multiple time points before and after an intervention
 - Typically, at equally spaced times
- Often no control group
 - A policy is implemented at the population-level
 - Health care reform conducted system-wide
 - (Difference-in-differences regression or Comparative ITS* when control group exists)
- Randomization is not feasible, ethical, affordable

Modeling ITS Data

- Simple comparisons of the mean pre- and post-intervention are not sufficient
- One of the most common ways to analyze ITS data is via segmented regression
 - Accounts for underlying trends and correlation
 - Quandt, R. E. (1958). The estimation of the parameters of a linear regression system obeying two separate regimes. *Journal of the american statistical association*, 53(284), 873-880.
 - Thistlethwaite, D. L., & Campbell, D. T. (1960). Regression-discontinuity analysis: An alternative to the ex post facto experiment. *Journal of Educational psychology*, 51(6), 309.
 - Frequently used in health services research, economics and education



The Impact Model



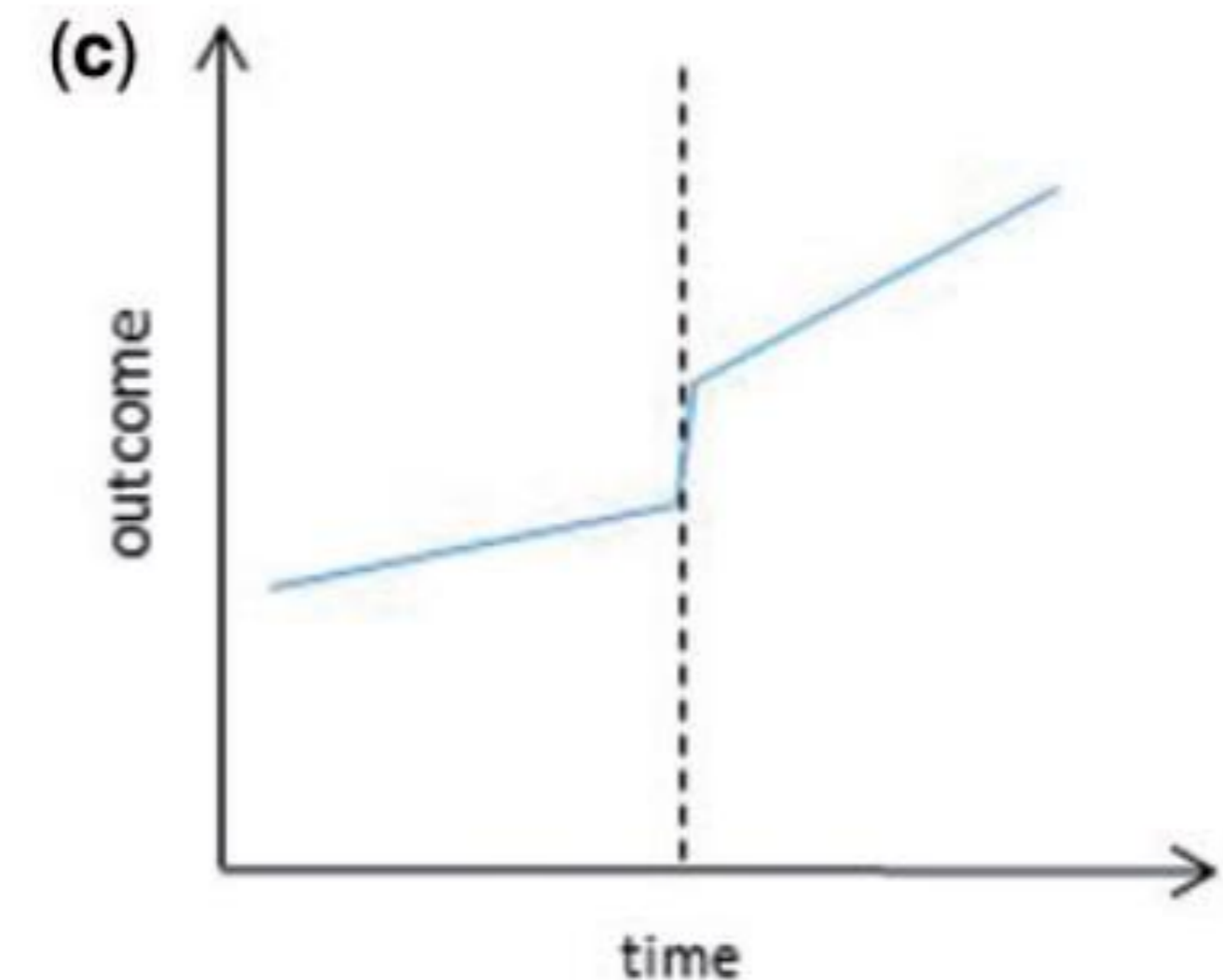
- Hypothesize how the intervention will impact the time series
- Some folks say this is a must
 - Quasi-experimental vs. usual associations
- Some folks think you can let the data tell you

Segmented Regression

- We will assume a linear flexible impact model
- Let y_t denote the outcome of interest at time point $t \in \{1, \dots, n\}$
- n is the length of the time series
- Then, the general segmented regression model is:

$$y_t = \mu_t + \epsilon_t$$

where μ_t is the mean function at time point t and ϵ_t is the stochastic component or error term at time t .



Segmented Regression Mean Function

- The mean function is

$$\mu_t = \begin{cases} \beta_0 + \beta_1 t, & t < \tau - k \\ (\beta_0 + \delta) + (\beta_1 + \Delta)t, & t \geq \tau + k \end{cases}$$

where k is equal to zero if the change point, τ , is assumed known

- We can write the mean function as:

$$\mu_t = \beta_0 + \beta_1 T + \delta X_t + \Delta T X_t,$$

where T is the time since the first observation, X_t is a dummy variable equal to 1 in the post-period.

- There is another common parametrization that tracks time from intervention; they are equivalent.

Segmented Regression Error Term

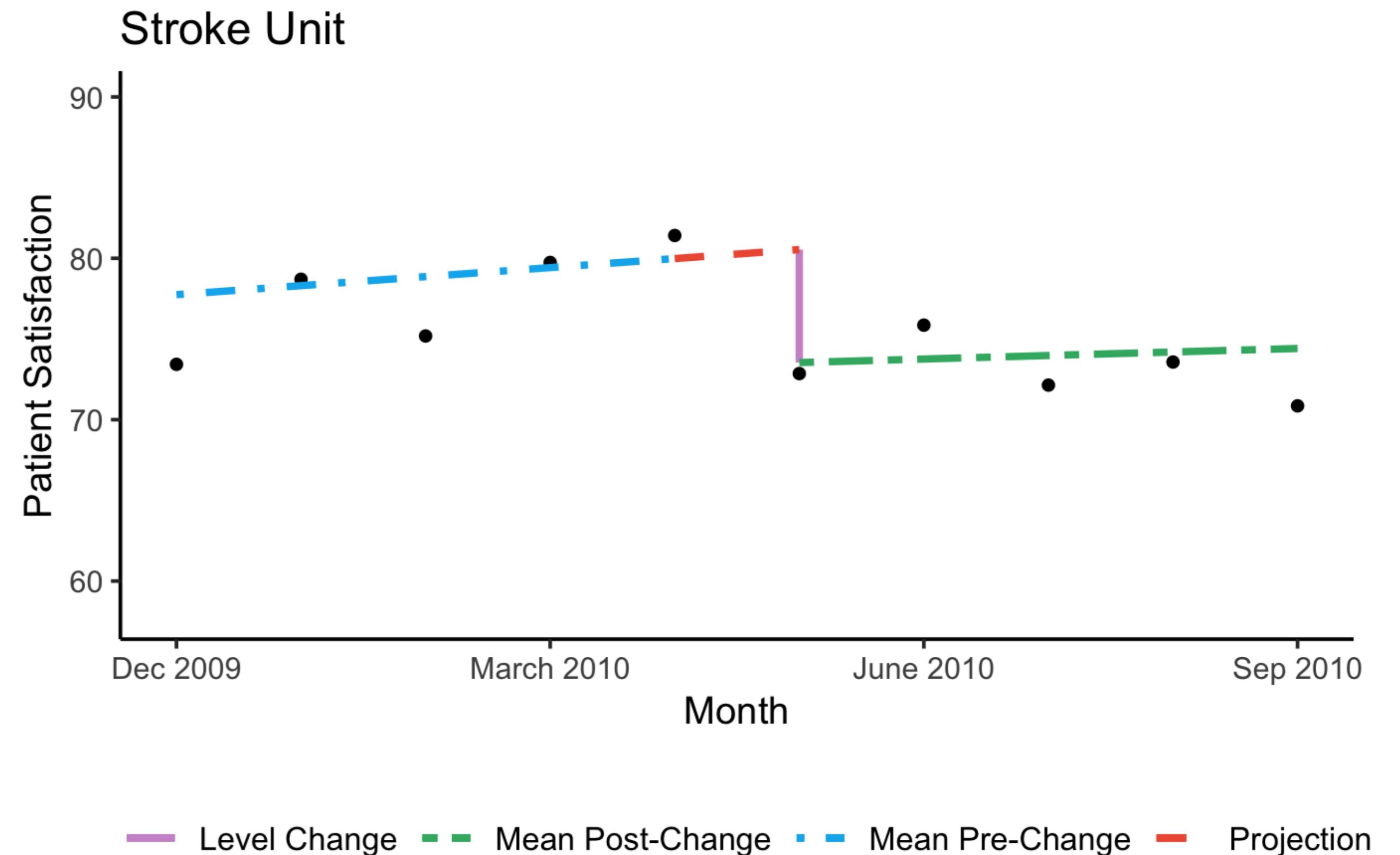
- The error term or stochastic process accounts for the variability and correlation of the outcome.
- If the ITS data are independent, $\epsilon_t \stackrel{iid}{\sim} N(0, 1)$ for all t .
 - Frequently assumed
 - Post-hoc tests for correlation exists
- When ITS measurements are not independent, the stochastic process may be modeled with an appropriate ARIMA process.
- I have typically modeled the error term as an AR(1) process:

$$\epsilon_t = \phi \epsilon_{t-1} + e_t,$$

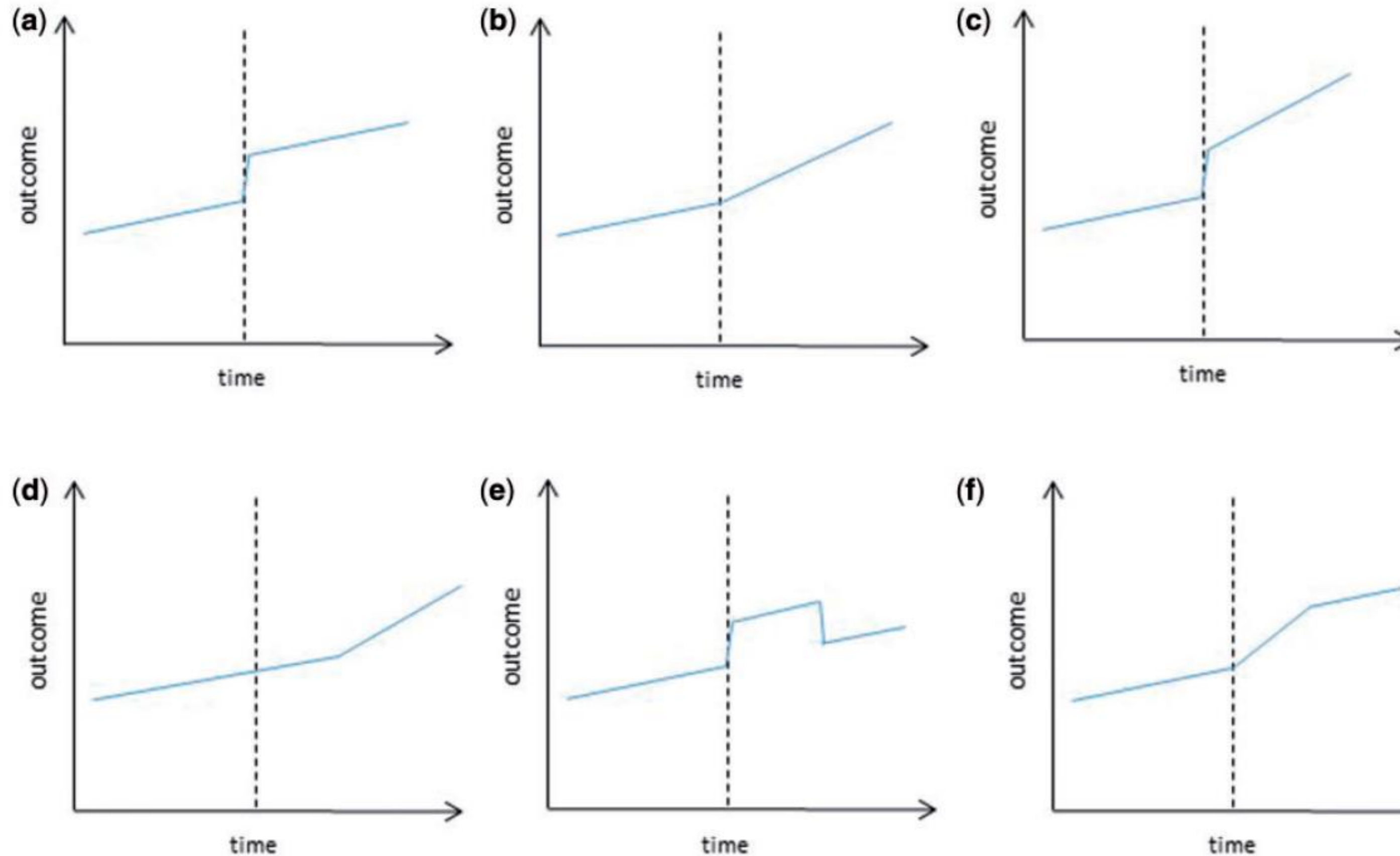
with $e_t \stackrel{iid}{\sim} N(0, \sigma_w^2)$, $\phi \in (-1, 1)$, and $t \in \{2, \dots, n\}$.

Quantities of Interest – Intervention Impact Measures

- Necessary to report 2 measures when interpreting the results of an ITS study
- Level change:
 - Discontinuity at change point
 - $\delta + \Delta \tau$
- Trend change:
 - Slope change
 - Δ



The Impact Model



The quantities of interest will vary depending on the choice of impact model

And on whether a control group is present:

subtract control rate from intervention rate, fit a single model to measure the change in differences
DID / CITS methods

Additional Statistical Issues – See Bernal et al. 2017 Paper

- Model diagnostics
 - Check that variance is reasonable
 - Check that residuals behave as white noise and that there is no more stochastic patterns left
- Seasonality
- Time-varying confounders
- Discrete outcomes
- Complicated correlation structures



Bernal, J. L., Cummins, S., & Gasparrini, A. (2017). Interrupted time series regression for the evaluation of public health interventions: a tutorial. *International journal of epidemiology*, 46(1), 348-355.

Limitations of Segmented Regression

- Assumes:
 - A change point exists
 - Complete separation between pre- and post-intervention phases
 - Focuses on capturing a change in the mean function
 - Ignores changes in variability and correlation
 - A single time series/outcome
- Full disclaimer – We have solved most of these issues. See:
 - Cruz, M., Gillen, D. L., Bender, M., & Ombao, H. (2019). Assessing health care interventions via an interrupted time series model: study power and design considerations. *Statistics in medicine*, 38(10), 1734-1752.
 - Cruz, M., Bender, M., & Ombao, H. (2017). A robust interrupted time series model for analyzing complex health care intervention data. *Statistics in medicine*, 36(29), 4660-4676.

How to Analyze Data

- Estimation with non-independent errors:
 - Can do two-stage modeling:
 - First stage model the mean function via simple linear regression (OLS)
 - Second stage model the residuals via simple linear regression
 - Can model both the mean function and error terms simultaneously
- Estimation with independent errors:
 - Can use simple linear regression
 - Make sure to check the residuals with acf and pacf plots!

Code and Packages

TABLE 1 The limitations and advantages of ITS packages that focus on segmented regression and gives a few papers in which the packages have either been proposed or used

Package	Papers	Advantages/Description	Limitations
SAS PROC AUTOREG ²¹	Penfold & Zhang ⁷ Shardell et al ²² Parianti et al ²³	<ul style="list-style-type: none"> • Estimation and prediction of linear regression models with autoregressive errors. • Estimation and testing of general heteroscedasticity (change in variance). 	<ul style="list-style-type: none"> • No intervention analysis.
SAS PROC ARIMA ²¹	Shardell et al ²²	<ul style="list-style-type: none"> • Analyzes and forecasts time series, transfer functions, and intervention data using ARIMA and ARMA models. 	<ul style="list-style-type: none"> • Assumes intervention time is fixed with an immediate effect. • Assumes one overall correlation structure.
SAS ETS ²¹	Cable, ²⁴ Mahamat et al, ²⁵ and Aboagye-Sarfo et al ²⁶	<ul style="list-style-type: none"> • Same as the above 2 entries; SAS PROC ARIMA and SAS PROC AUTOREG are part of SAS ETS. 	<ul style="list-style-type: none"> • Fixed intervention time with immediate effect. • One overall correlation structure
Stata ITSA	Linden ²⁷	<ul style="list-style-type: none"> • Single and multiple group comparisons. • Estimates treatment effects for multiple treatment periods. 	<ul style="list-style-type: none"> • Fixed change point. • One overarching correlation structure.
segmentedR	Muggeo ²⁸	<ul style="list-style-type: none"> • Adjust for overall autocorrelation. • Estimates piecewise regression models with a fixed number of discontinuities, or interruptions. 	<ul style="list-style-type: none"> • No modeling of correlation structure. • Assumes data are independent.

Abbreviations: ITS, interrupted time series.

We have also created a toolbox with flexible modeling approaches:

- Cruz, M., Pinto-Orellana, M. A., Gillen, D. L., & Ombao, H. C. (2021). RITS: a toolbox for assessing complex interventions via interrupted time series models. *BMC Medical Research Methodology*, 21(1), 1-15
- https://biostatistics-kaust.github.io/robust_time_series_toolbox/

Threats to Validity

Contemporaneous
QI programs
(competing
interventions)

Heterogeneity in
the composition of
the “population”

Eligibility, attrition,
selection

- Maturation
- Mortality

Instrumentation

Speed of
implementation
and delayed
effects

Short time series

Suitability of
control population

Competing Interventions



Contemporaneous QI initiatives or programs



Competing interventions **MUST** overlap the study time to be confounders



Not to be confused with an overall (e.g., national) trend

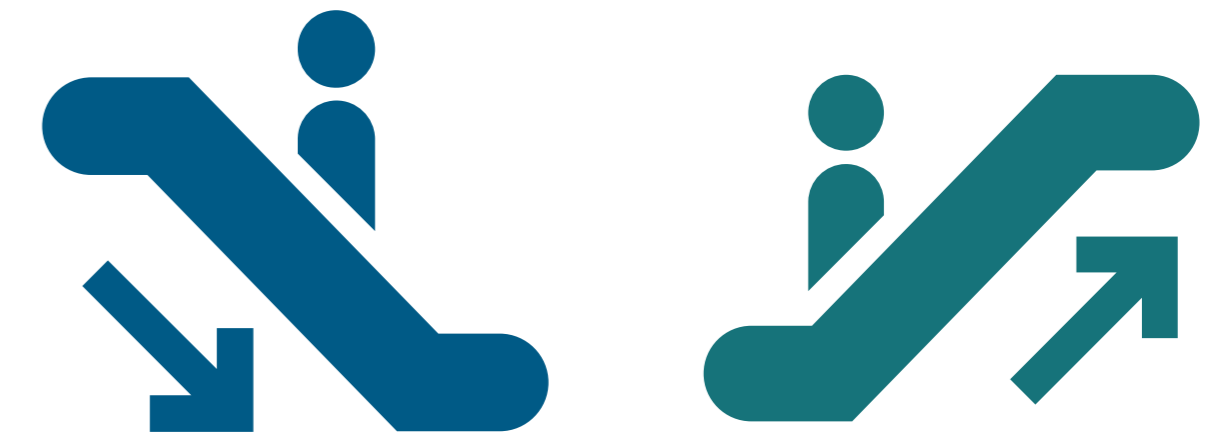
We can model the secular trend explicitly

Population Heterogeneity (Selection)

- Composition of population changes over time
 - Within-population confounders are no longer constant (controlled)
 - Change in risk factors over time may be the cause of increasing/decreasing rates rather than the intervention or policy
- Potential solutions
 - Standardize population to the intervention period (weight)
 - Similar to standardized mortality ratios
 - Limit the population to those individuals observed in all time periods of the analysis (fixed cohort) – not ideal

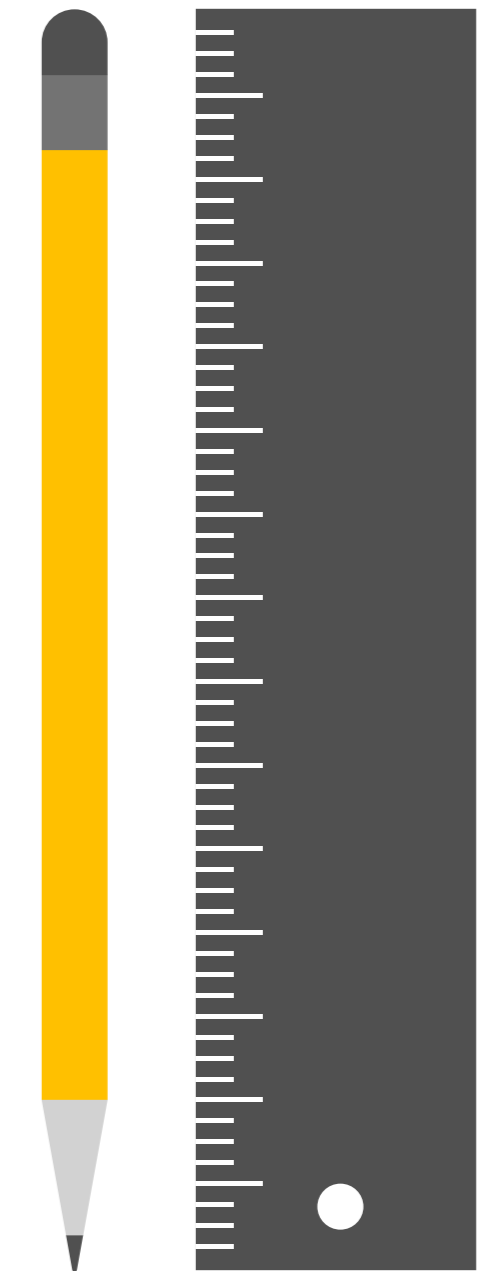
Maturation & Attrition

- Particular problem for child and adolescent research
 - Youth age out of and into the population at risk
 - Youth at risk leave the population
- Rolling cohort often better than a fixed cohort
- Can stratify by age group
- Can use Inverse Probability Weighting (IPW) to account for attrition

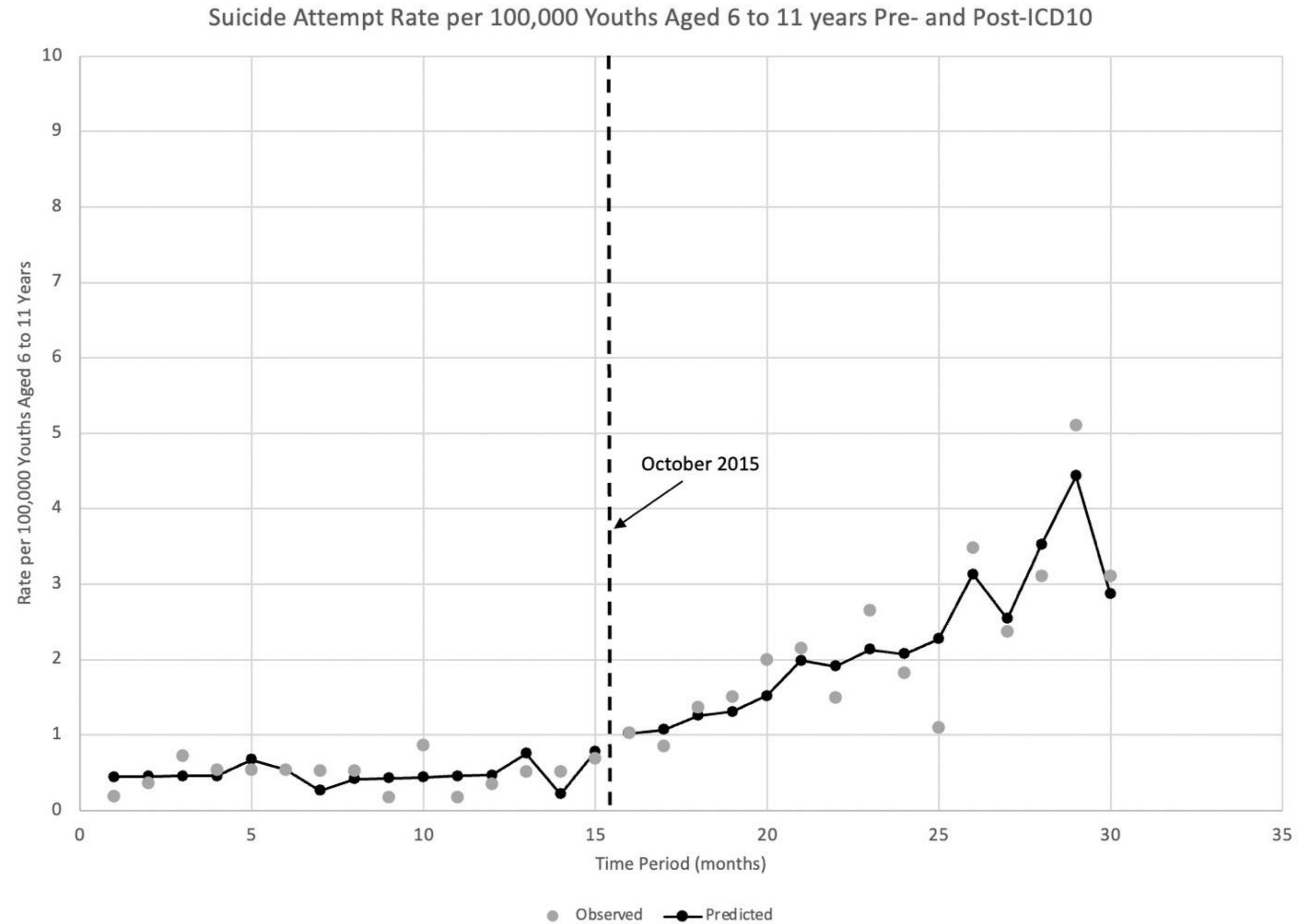


Instrumentation (Measurement)

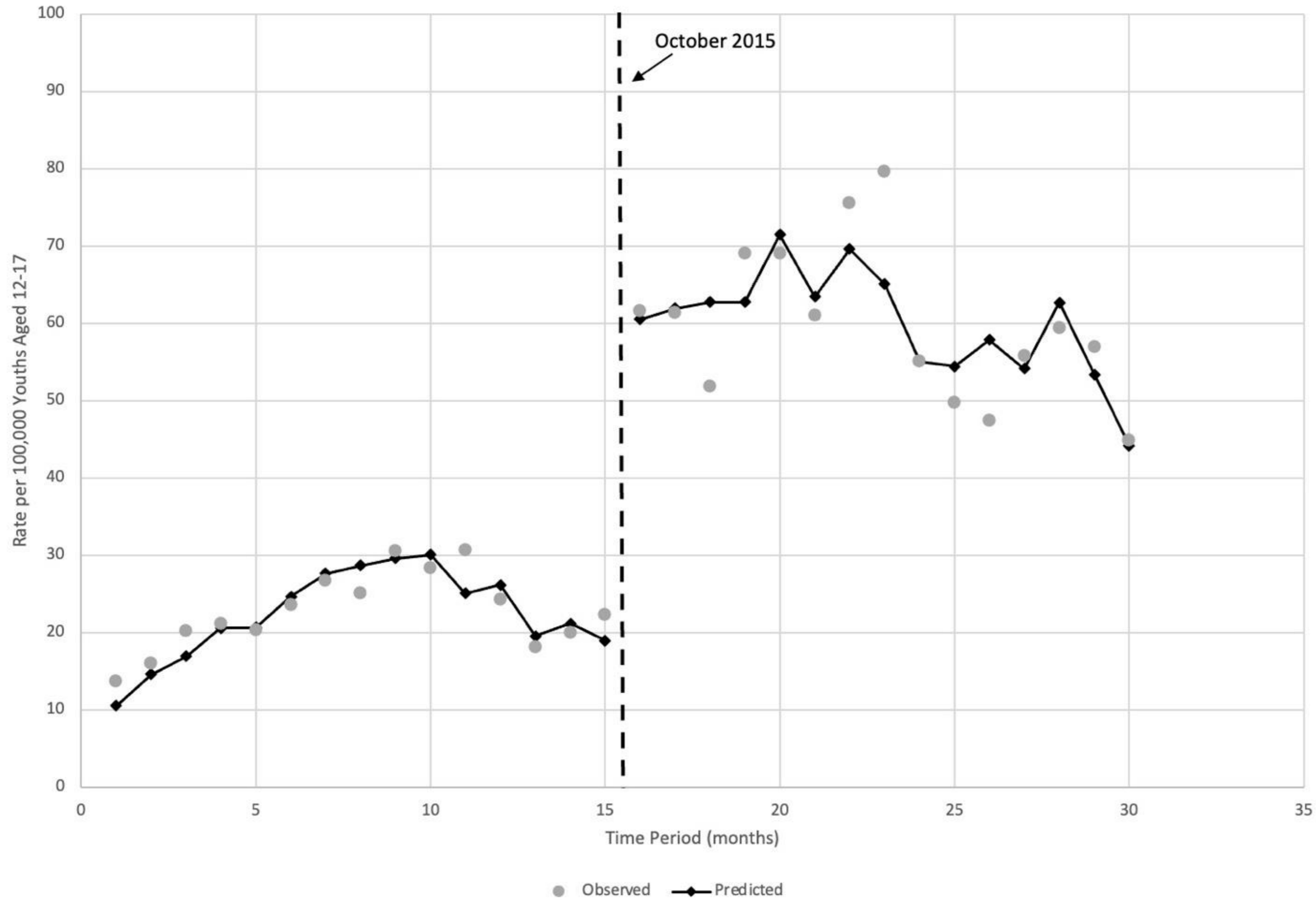
- Ability (effort?) to measure the event changes
 - Transition to EHR
 - Changes in coding (ICD9 – ICD10)
 - Introduction of a new instrument (e.g., screening)
 - Change in definition of an event
- Be careful that your intervention does not directly impact your ability to measure (e.g., intervention to reduce unnecessary visits)
 - Example: switch to telehealth during COVID
 - Coding of video and phone visits (and chat encounters)



Pre-post ICD10-CM Self-harm Rates in Youths 6-11



Suicide Attempt Rate per 100,000 Youths Aged 12-17 Years Pre- and Post-ICD10



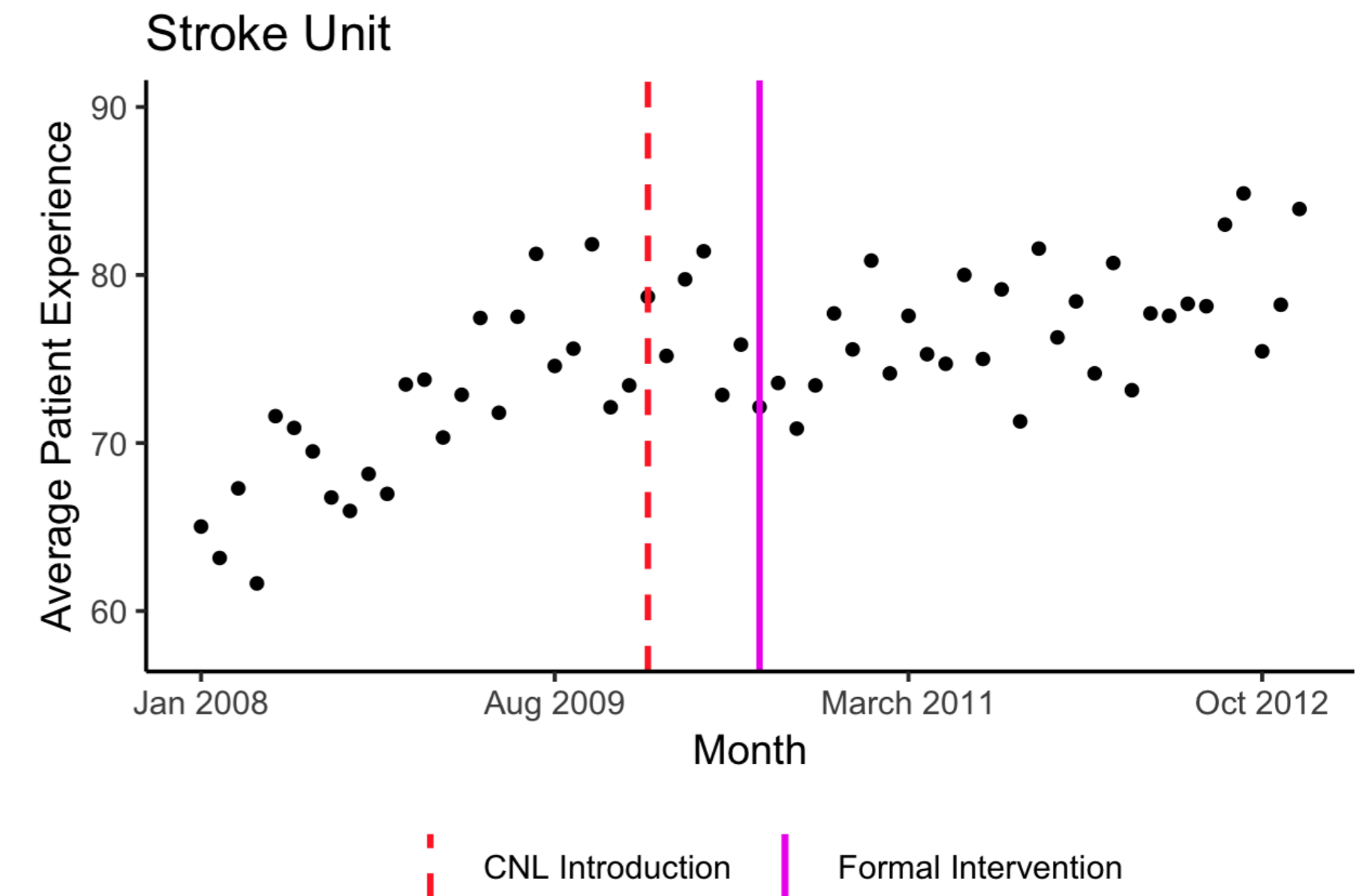
Pre-post ICD10-CM Self-harm Rates in Youths 12-17

Other Threats to Validity

- Speed of implementation and delayed effects
 - Choose impact model appropriately!
- Short time series
 - Statistical power!
- Suitability of control population
 - Are pre-period trends similar?
 - Are populations similar?
- Multiple sites with staged Roll-out
 - Changes often occur at “easiest” sites first
 - Implementation issues often resolved as additional sites come “online” (i.e., learning occurs)
 - Censor observations around the go-live date
 - Conduct separate ITS by site
 - “Center” ITS analyses on the implementation time

Case Study: Assessing the Impact of a New Nursing Care Delivery Model

- Data from a single Michigan healthcare system
- Study aimed to determine the influence of a new nursing care delivery system
- Outcomes: Patient experience survey scores
 - Top-box scores
 - Collected monthly for 5 years
 - Collected at 10 hospital units
 - 7 experience scores



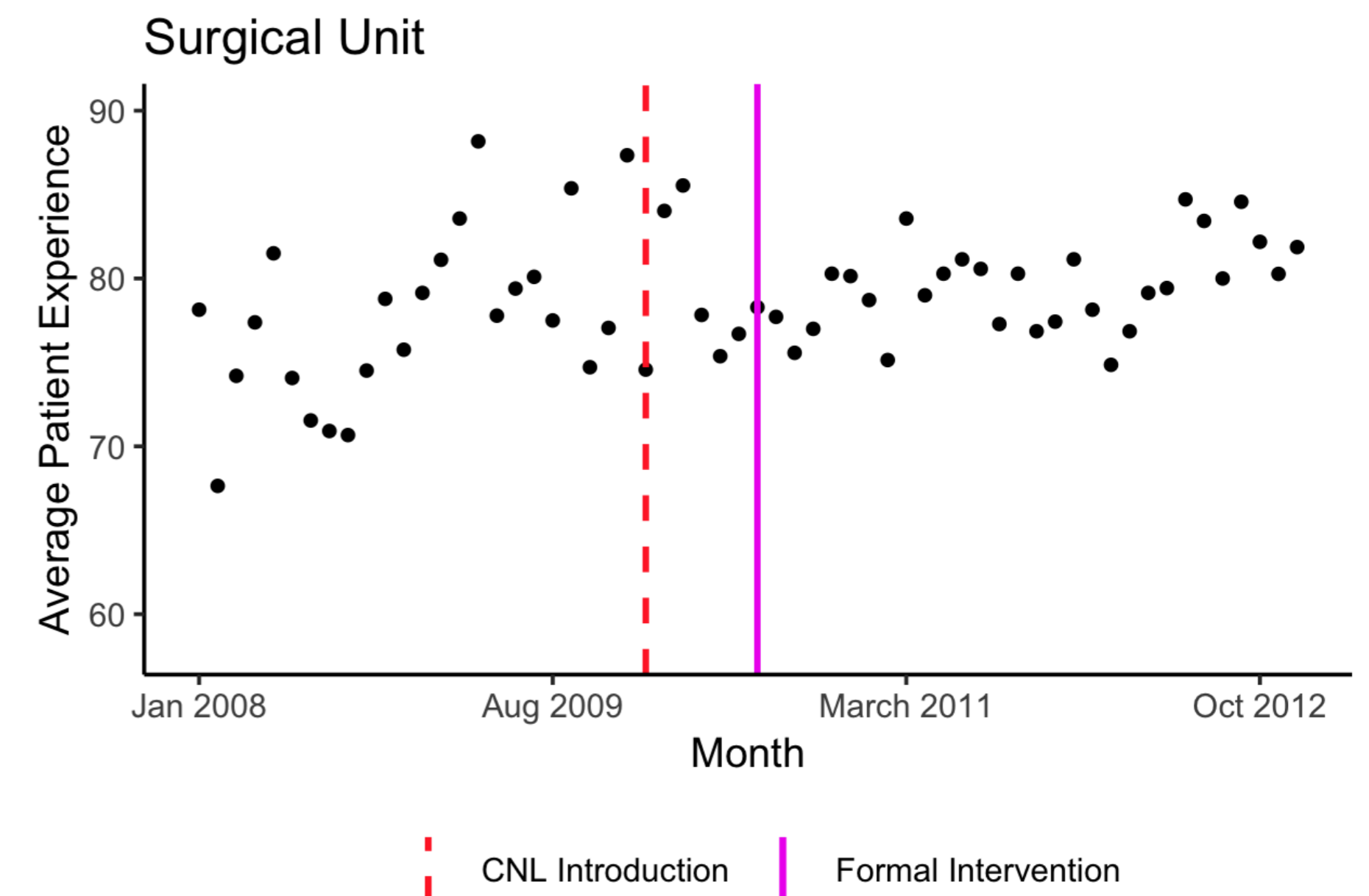
Patient Experience

1. Effective Nurse Communication

- always** ← %
- usually
- sometimes
- never

Intervention

- The intervention was the implementation of the Clinical Nurse Leader (CNL) integrated care delivery model.
- Had 3 aims:
 1. Lead and sustain interdisciplinary collaboration
 2. Laterally integrate services across disciplines and care settings
 3. Use evidence-based criteria to measure quality of care



Group Exercise 1

1. Read the CNL paper up to the results (or ask me questions about the design/study).
2. Use what you know about ITS designs/data/methods and threats to validity to review the manuscript.
3. Report back to the larger group.

System- and Unit-Level Care Quality Outcome Improvements After Integrating Clinical Nurse Leaders Into Frontline Care Delivery

Miriam Bender, Elizabeth A. Murphy, Maricela Cruz, Hernando Ombao

[Authors and Affiliations >](#)

JONA: The Journal of Nursing Administration 49(6):p 315-322, June 2019. | DOI:

10.1097/NNA.0000000000000759

Group Exercise 2

The CNL intervention was rolled out to 4 health systems across the United States.

1. Design an ITS study to evaluate the CNL intervention across these 4 health systems.
 - Considerations:
 - How will you implement the intervention?
 - What will you measure? What are your outcomes? Are they aggregated?
 - What is your time unit (e.g., month or week) and study period length?
 - Who is the population?
 - What are the potential threats to validity?
2. Report back to the larger group.

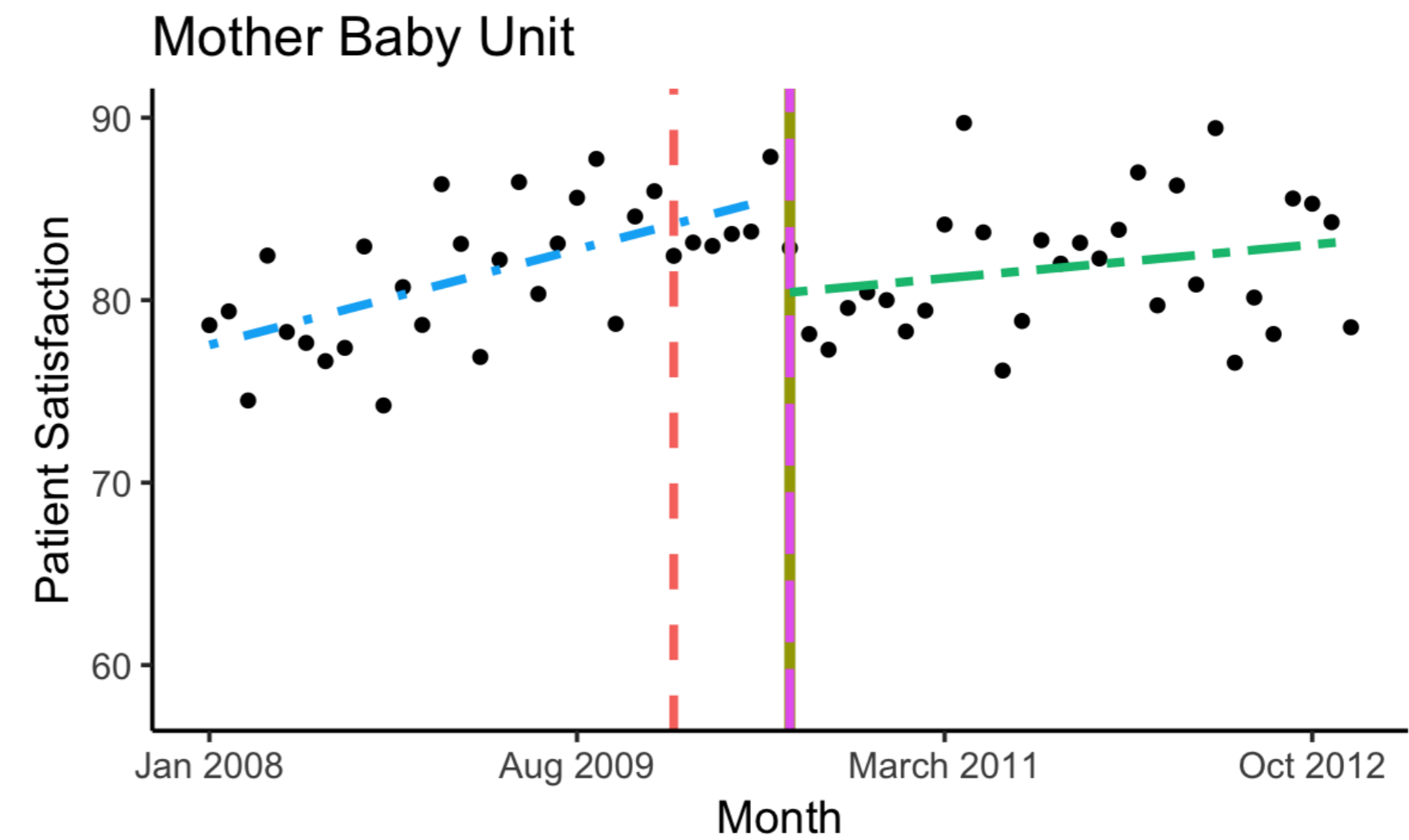
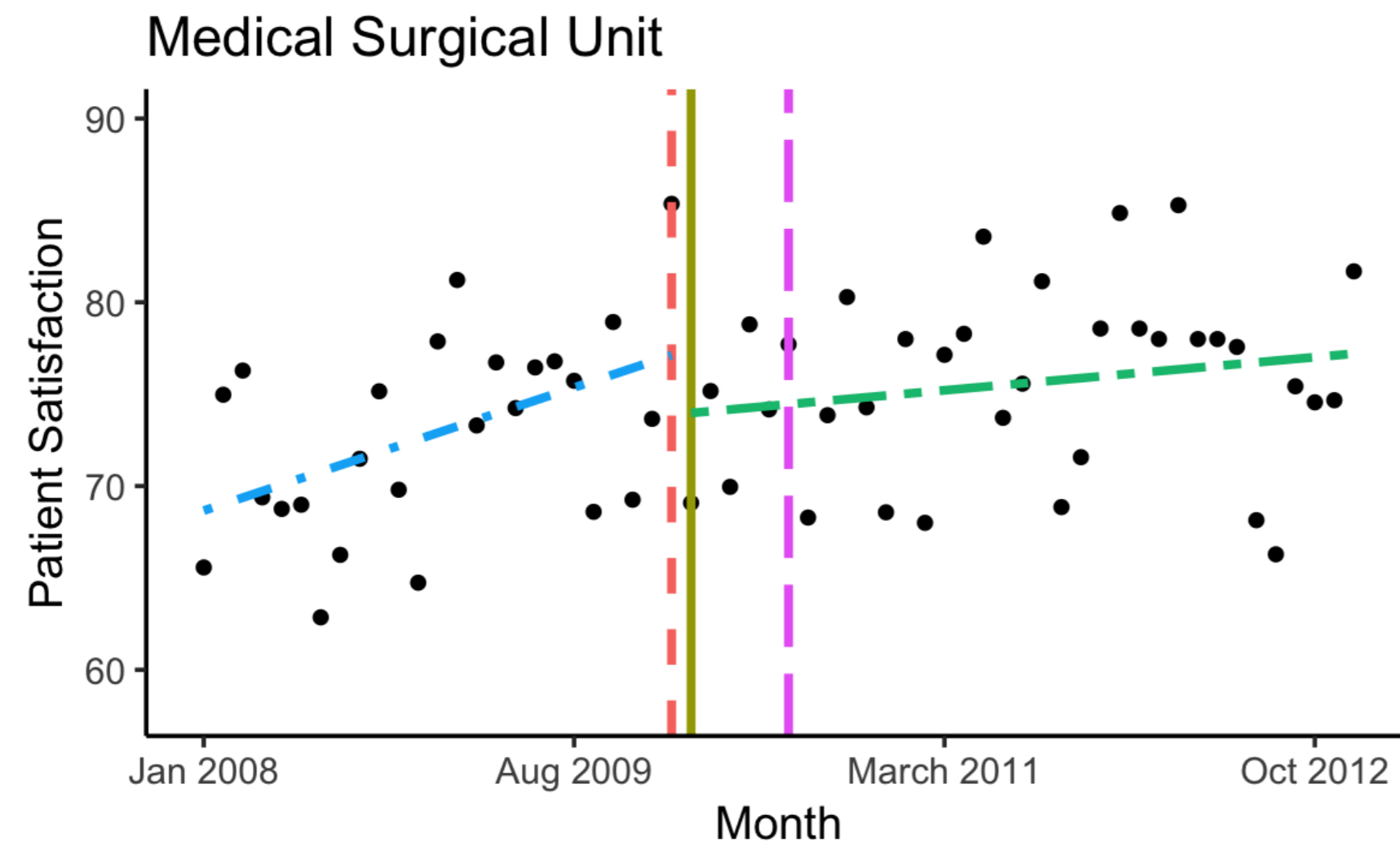
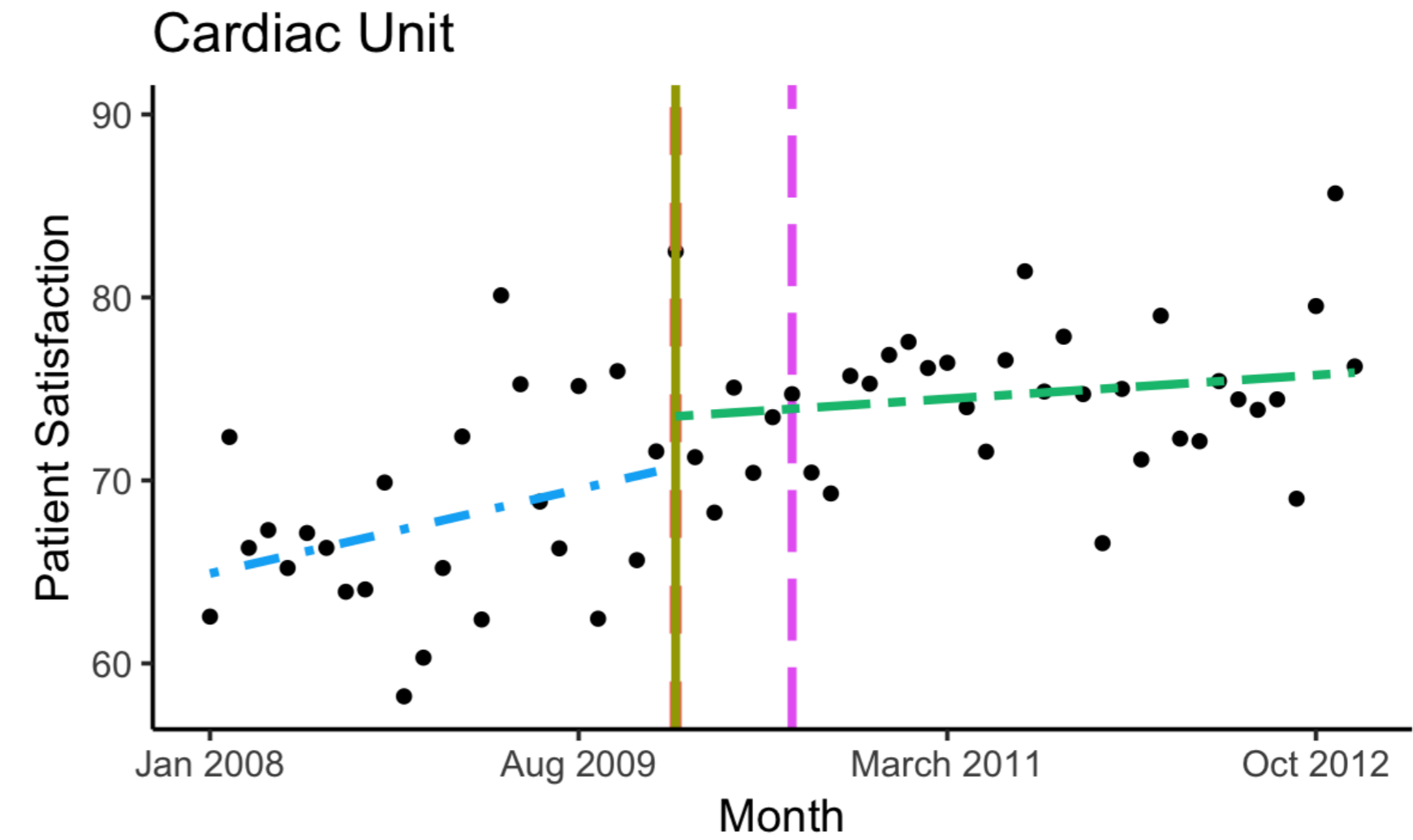
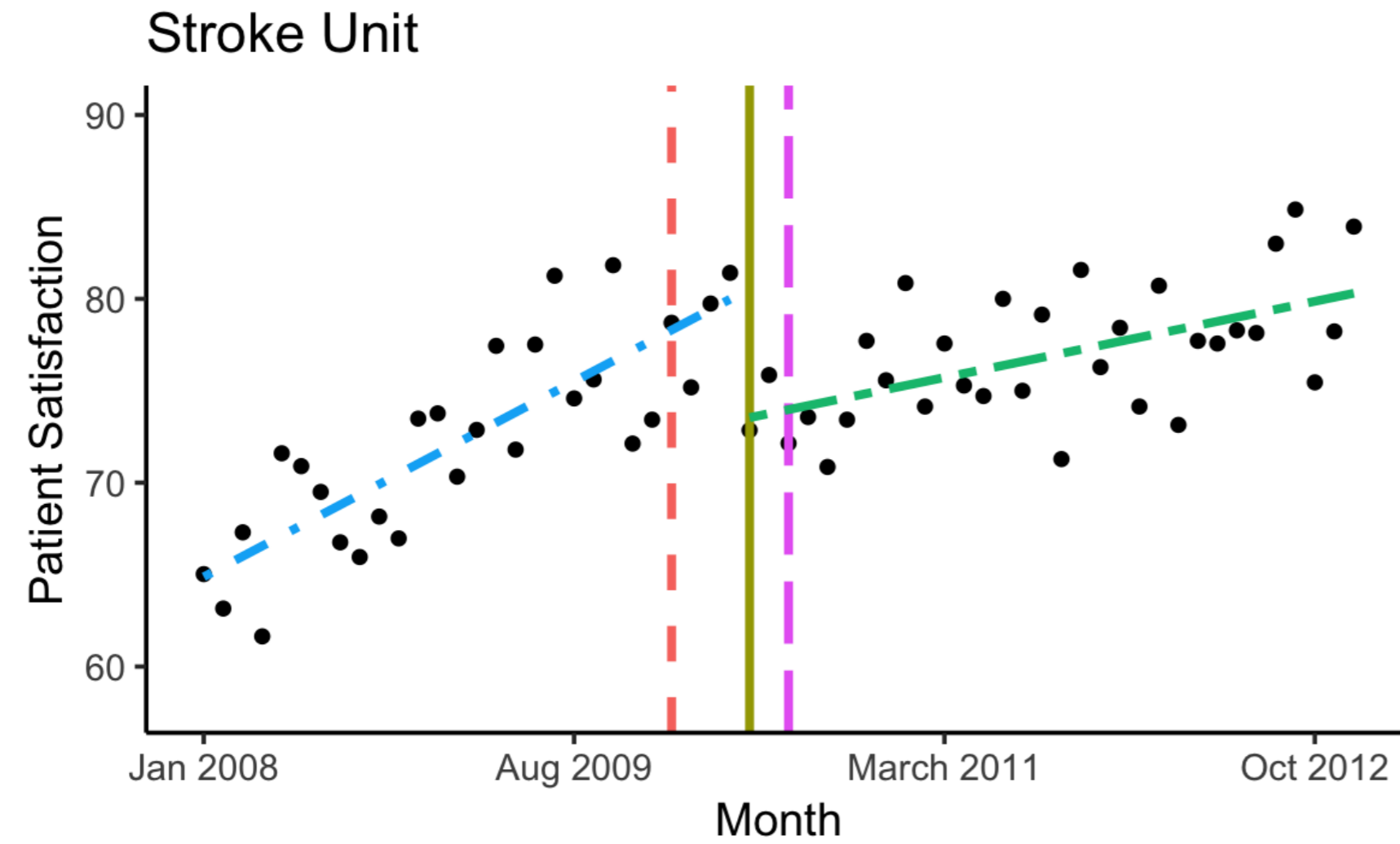
Thank you!!

Email: Maricela.F.Cruz@kp.org

Please evaluate this session here:



Mean Function Results



- - - CNL Introduction
 | Estimated Change Point
 - - - Estimated Mean Post-Change
 - - - Estimated Mean Pre-Change
 - - - Formal Intervention